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Assessment of the wind energy resource in the South Banat region, Serbia

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ABSTRACT

The wind energy resources in the South Banat region are analyzed. The analyses have been carried out on the basis of the wind parameter measurements at the site of village Bavanište. The data were collected at the heights of 10, 40, 50, and 60 m during 2009 and 2010. The statistical analyses of the measured data covered the wind speed and direction, average wind speed and power density, and Weibull distribution parameters (c and k). On the basis of the determined standard deviation of the wind speed, an analysis is performed of the wind turbulence at the measurement site. Based on the method of sum of least squares, a mathematical method for estimation of the vertical wind speed profile has been developed. By applying this model, an analysis of the vertical wind speed profile at the measurement site has been performed. On the basis of the available measurement data, the electrical energy production in the targeted region by three test models of the wind turbines has been estimated. The obtained results show that the region of South Banat possesses good wind energy potential and that it represents a promising region for development of the projects of wind farms.

Contents

1. Introduction

Electricity production in the Electric Power System of Serbia (EPS) predominantly relies on thermal power plants (TPP) burning lignite. The actual installed power (net output) of the EPS' production capacity is 7124 MW: 3936 MW – TPP burning lignite, 353 MW – combined heat and power stations (CHP) using liquid or gaseous fuel, 2835 MW – hydro power plants (run-of-river hydro power plants – 1849 MW, hydro power plants with reservoirs – 372 MW, and pumped storage power plants – 614 MW). In 2009 total energy production of EPS was around 36,000 GWh, of which 69% was produced in TPP by burning 37.78 millions of tons of lignite,

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accompanied by emission of harmful gases [1]: around 29 million tons of CO_2, 58,000 tons of SO_2, and 264,000 tons of NO_x.

The greatest share in the electricity consumption in Serbia is taken by households (53.07% in 2009). The average annual index of growth of electricity consumption in Serbia was around 1% over the past decade, but it is expected that further industrial growth will increase this index. The increased demands for electricity are met at present by increasing production of TPP. In 2001 production of electrical energy by TPP was 18,974 GWh, while in 2009 it was 24,880 GWh, an increase of over 31% [1]. This structure and orientation of electrical energy production in Serbia are not sustainable both from the ecological point of view and from the point of view of exhaustion of the coal resources. The available reserves of lignite in Serbia which are usable for production of electrical energy, estimated at 1.8 billion tons, would be, with the present dynamics of exploitation, exhausted within the next 50 years.

Realizing the problems associated with exhaustion of fossil fuels and following the world developments in the area of electrical energy production, Serbian Government have issued a decree on subsidizing production of electrical energy from renewable energy sources (RES), such as: wind, solar, small hydro, biomass, and biogas. According to this decree, subsidizing electrical energy production from wind is according to the model fid-in-tariff, with the guaranteed price 95 Euro/MWh for the period of 12 years [2]. The Energy law has also been changed with the aim of stimulating the development of renewable energy sources. Article 34 of the Energy law sets obligations to *Transmission System Operator* (TSO) *and Distribution System Operator* (DSO) to allow access of third parties to the grid. Also, purchase of electricity produced from RES is obligatory [3]. The renewable energy policy in the Republic of Serbia is described in detail in [4].

Despite the existence of relatively good legal and economic frameworks for development of projects of wind power plants, not one wind turbine has been installed in Serbia until now. One of the main reasons for this delay in the investments in development of wind power plants is inadequately investigated wind potential.

Several studies concerning global wind potential in Serbia have been made. These investigations, presented in [5], show that the north-eastern part of Serbia, called South Banat, has the best potential of wind energy in Serbia. According to these investigations, the average annual density of wind power in this region, estimated at the height of 100 m (above the ground level), is in excess of 500 W/m^2. Investigations carried out in study [6] also point out at this region as regards the possibility of using potential wind energy, estimating that the average annual wind power in this region, at the height of 100 m, is in excess of 300 W/m^2. Similar results have been obtained in study [7], where it has been estimated that the average annual wind speed in this region at the height of 100 m is in excess of 6 m/s, and the corresponding density of wind power is higher than 250 W/m^2. In [8] the region of South Banat is favored as being perspective for developing the projects of wind power plants in Serbia, both from the point of view of available wind resources and from the point of view of other key aspects, such as road infrastructure and conditions for wind farm grid connection. The estimated average annual wind speed in this region at the height of 50 m from the ground is about 5.5 m/s, and the corresponding average density of wind power is higher than 250 W/m^2. All these studies are based on the standard hydro-meteorological measurements carried out by meteorological stations at the height of 10 m. The locations of these measurement stations and the height of the measurements are not representative for making a reliable estimate of the wind energy potential in this region. For this reason the estimated wind potential in these studies is only of an approximate character.

The aim of this paper is to evaluate the feasibility of a wind park project in the region of South Banat, which is located in the province of Vojvodina in the north-eastern part of Serbia. The analyses are based on the dedicated measurements of wind speed in the targeted region by means of a 60 m high measurement mast. The measurements have been carried out over the period of two years, 2009–2010. This is the first report assessing the wind energy potential in Serbia using on the site measured wind speed data.

2. Geographic, topographic, and climatic characteristics of the South Banat region

South Banat region is situated in the north-eastern part of Serbia, latitude 44.7–45.3°N, longitude 20.5–21.5°E, approximately. Topography of the region shows a very flat terrain. The height varies from 70 up to 200 m above sea level. The soil is of agricultural character with several types of crops being cultivated (wheat, maize, sunflower, soy, etc.). The region has a developed road infrastructure which, together with the river Danube and the port of Pančevo, which is located in this region, ensures cheap transportation of equipment of the perspective wind power plants.

The area of interest is influenced by the regional wind called košava. It is a cold dry wind with a prevailing flow from the south-east direction. Košava follows the Danube, northwest through the Iron Gate valley where it gains a jet effect, and then continues towards Belgrade.

The average temperature ranges are from 2 to 12 °C for the winter months and 11–21 °C for the summer months. The highest recorded temperature is 41 °C and the lowest recorded temperature is −23.7 °C. The average number of days annually having maximum temperature above 30 °C is 30, the average number of days annually having maximum temperature above 25 °C is 85. The average air humidity in January is 85%. Taking into account this high humidity, the frost can be expected on average 20 days annually. These values have been obtained by the measurements in the regional meteorological station Banatski Karlovci which cover the period 1985–2010.

3. Description of the measurement site and measuring equipment

A 60 m tube anemometer mast is installed on the site near Bavanište village. The exact latitude and longitude of the mast are N44°50.850′, E020°53.465′. The site altitude is 98 m above sea level. The measuring mast is positioned at an open terrain location having no obstacles. By the close and far topography the site can be described as a very flat area without any significant slopes or other tricky surface elements, as shown in Fig. 1. Taking into account topographic characteristics of the terrain, the measurement data are representative for making estimates of the wind potential of the South Banat region.

The measurements of wind speed have been carried out at four different heights: 10, 40, 50, and 60 m by a digital cup anemometer (model #40c NRG Systems). Measurements of wind direction have been performed at two heights, 60 m and 50 m by means of a wind vane (model #200P NRG Systems). One temperature sensor (model #110 s NRG Systems) and one air pressure meter (model BP 20 NRG Systems) were installed at the height of 5 m. The best practices for wind resource assessment suggest that measurement of temperature and air pressure is carried out as close to the wind turbine hub height as possible, but in this case, for technical reasons (lengths of the connecting cables of sensors), the measurement height was limited to 5 m.

Lay out of the measuring equipment has been in accordance with standard IEC 61400-12-1 [9]. A data logger (model NRG Symphonie) made records of 10 min average and 2-s extreme (min and max) values of wind speed, wind direction, air temperature, and air pressure. Also, the data logger carried out calculation of

Fig. 1. Measurement mast at the site Bavanište (South Banat region).

the standard deviation of wind speed at all measurement heights for each 10 min interval.

4. Theoretical models for analysis of the measured data

This section presents the methodology and the corresponding theoretical models applied for the statistical analysis of the measured data, as well as the model for analyzing vertical profile of the wind speed based on the method of least squares. A methodology for estimation of the annual production of electrical energy for the selected wind turbines is also presented. The results of all these calculations are presented in Section 5.

4.1. Weibull statistics of wind speed

The Weibull distribution has been widely used to describe the probability density of the wind. These statistics are used in the analyses of the wind energy resources carried out in various parts of the World. Some of these investigations were presented in the literature [10–24]. Carta et al. [24] reviewed and compared the most widely used and accepted distributions in the literature specialized in wind energy and the methods utilized for estimation of their parameters. They concluded that the Weibull distribution had a number of advantages with respect to the other analyzed probability density functions.

The general form of Weibull distribution for the wind speed is given by:

$$f(V) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1}\exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{1}$$

where $f(V)$ is the probability density function, c and k are, respectively, the scale and shape parameters.

For the purpose of estimating the parameters of Weibull distribution c and k several methods have been developed. Stevens and Smulders [25] obtained values of the Weibull distribution parameters using five different methods: moments, energy pattern factor, maximum likelihood, Weibull probability, and the use of percentile estimators. In the analysis of the measurement data in this work the use of the maximum likelihood method has been made because it turned out optimal, as shown by a comparative analysis carried out by Seguro and Lambert [26].

To estimate Weibull parameters from the wind speed data by using maximum likelihood method, the following equations are used:

$$k = \left[\left(\frac{\sum_{i=1}^{N} V_i^k \ln(V_i)}{\sum_{i=1}^{N} V_i^k}\right) - \left(\frac{\sum_{i=1}^{N}\ln(V_i)}{N}\right)\right]^{-1}, \tag{2}$$

$$c = \left(\frac{1}{N}\sum_{i=1}^{N} V_i^k\right)^{1/k} \tag{3}$$

where V_i is the average wind speed of the ith 10 min interval and N is the total number of nonzero wind speed data points.

4.2. Wind power density

The average wind power density ($\overline{P}$) is the average power available per unit area of the turbine rotor, and can be calculated as:

$$\overline{P} = \frac{1}{2}\frac{1}{N}\sum_{i=1}^{N}\rho_i V_i^3, \tag{4}$$

where V_i and ρ_i are the wind speed and air density over the corresponding ith 10 min time interval at the hub height H, respectively; N is the total number of wind speed data points over the time interval considered.

Air density is time-variable and for its calculation it is necessary to measure several meteorological parameters. Dominant influence is due to the pressure, temperature, and humidity of the air. Calculation of air density on the basis of these three parameters is described by relatively complex mathematical relations available in the literature [27]. If measurement data on relative humidity of the air are not available, as in the present analysis, then, assuming that the air is dry, the air density can be calculated on the basis of the measurement of the air temperature and pressure by the following equation:

$$\rho_i = \frac{p_i}{RT_i}, \tag{5}$$

where p_i, T_i and ρ_i are respectively the pressure (Pa), temperature (K), and air density (kg/m^3) in the ith 10 min time interval at the wind turbine hub height H where the analysis is carried out, and R is the specific gas constant for the air (287 J/kg K). The assumption that the air is dry introduces a certain error in the calculation, but for majority of locations this error is acceptable in the wind potential analyses.

If the measurement height H_0 is different from the wind turbine hub height H, it is necessary that for each data point the measured pressure and temperature are corrected to the hub height. Vertical temperature profile is variable in time and dependent upon atmospheric conditions [28]. Time variation of the vertical profile of temperature is quite difficult to assess since the atmospheric conditions (solar irradiation, cloudiness, air humidity, etc.) vary both at the daily and seasonal levels. For the purpose of estimating the vertical profile of temperature and stability of the atmosphere, it is useful to perform the measurements of temperature at different heights. If the measurements of temperature are performed at one height only, then an average vertical gradient of temperature can be adopted. In the present analysis, it has been assumed that the vertical profile of temperature is linear, having a constant gradient $\Delta T = -0.0066$ K/m. This value corresponds to the average

temperature gradient obtained on the basis of the meteorological measurement in the middle latitudes [28]. It should be mentioned that there may appear atmospheric conditions where temperature gradient can deviate significantly from the adopted value, or temperature profile is not linear, the appearance of temperature inversion included. In particular, such conditions may manifest themselves during winter time with high humidity, where a layer of fog is formed at the lower levels, but not at the upper levels. In the analyzed region these meteorological conditions usually appear at low wind speeds, thus they would not influence significantly the estimates of the wind energy potential.

According to ISO 2533 [29] and IEC 61400 [9], if the pressure sensor is more than 10 m below hub height, then for each data point i, the measured pressure is corrected to the hub height by the following equation [30]:

$$p_i = p_{i0}\left[1 + \frac{\Delta T}{T_{i0}}(H - H_0)\right]^{-g/\Delta TR} \tag{6}$$

where p_i (Pa) is pressure at hub height H, p_{i0} (Pa) is measured pressure at reference height H_0, T_{i0} (K) is measured temperature at reference height H_0 (in this analysis the measurement height for temperature and pressure was 5 m), ΔT is temperature gradient (−0.0066 K/m) and g is gravitational constant (9.806 m/s^2).

On the basis of relation (5) and assuming the model for the vertical temperature and pressure gradient and, the density at height H is evaluated, for each data point i, as follows:

$$\rho_i = \frac{p_{i0}\left[1 + \Delta T/T_{i0}(H - H_0)\right]^{-g/\Delta TR}}{R\left[T_{0i} + \Delta T(H - H_0)\right]} \tag{7}$$

4.3. Vertical wind speed profile

Accurate estimations of the wind power potential are based on the knowledge of the wind patterns at the height of the wind turbine hub. However, in practice, measurements of the wind speed are carried out at the heights lower than the height of the wind turbine hub, thus it is necessary to know the vertical wind speed profile.

There are several mathematical models describing the vertical wind speed profile [30]. In practice, the "logarithmic law" and "power law" are the most frequently used [31,32]. In this analysis, the power law model is used, given by the following relation:

$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^{\alpha}, \tag{8}$$

where V is the wind speed at height H, V_0 is the wind speed at reference height H_0, and α is a dimensionless coefficient (wind shear). There are many factors having influence on the vertical wind speed profile, i.e. on the value of coefficient α. The major influence is that of the surface roughness and atmospheric stability [30]. Seasonal variations of vegetation in the environment surrounding the measurement mast have influence on the variation of surface roughness. Daily and seasonal variations of atmospheric stability conditions influence the daily and seasonal variations of the vertical wind profile. For this reason, coefficient α is not unique and should be regarded as a time varying parameter dependent upon the time of day, season, direction and intensity of wind. In this work, estimation of parameter α has been done for each 10 min measurement interval. In the literature, coefficient α is usually estimated on the basis of the wind speed measurements performed at two heights [33–35]. In this paper a new model, based on the method of least squares which includes measurements performed at all measurement heights, is proposed.

For an arbitrary 10 min interval i equation (8) can be written in the following linearized form:

$$\ln(V_i) - \ln(V_{0i}) = \alpha_i(\ln(H) - \ln(H_0)). \tag{9}$$

If sets of measurement data for only two measurement heights are available, coefficient α is uniquely determined. If the wind speed measurement data are available for more than two heights, the system is redundant and it is suitable to apply the method of the minimum sum of least squares. By applying the method of the minimum sum of least squares to Eq. (9), one obtains Eq. (10), which defines an optimum estimate of coefficient α for each 10 min interval i:

$$\alpha_i = \frac{M \cdot \sum_{j=1}^{M} \ln(V_{ij}) \cdot \ln(H_j) - \sum_{j=1}^{M} \ln(H_j) \cdot \sum_{j=1}^{M} \ln(V_{ij})}{M \cdot \sum_{j=1}^{M} \ln(H_j)^2 - \left(\sum_{j=1}^{M} \ln H_j\right)^2}, \tag{10}$$

where V_{ij} is the wind speed in ith 10 min interval at the height H_j (j = 1, 2, . . ., M), M is the total number of heights where the measurements on the measurement mast have been carried out (M = 4 in this case).

On the basis of the measurement data on wind speed at heights H_j (j = 1, 2, . . ., M), by applying Eqs. (8) and (10) one can estimate, for each 10 min interval, the corresponding wind speed V_i at the selected height H:

$$V_i = V_{0i}\left(\frac{H}{H_0}\right)^{\alpha_i} \tag{11}$$

where V_{0i} is the wind speed at ith 10 min interval at reference height H_0 which corresponds to the highest measuring point (for the analyzed wind mast in the South Banat H_0 = 60 m). By applying this model, the set of measurement data on wind speed can be extended by a new column containing the estimated wind speed at the corresponding height H. The uncertainty of the wind speed estimate increases as difference between the measurement height H and reference height H_0 is increased. The practice shows that an acceptable accuracy of vertical extrapolation of the wind speed at majority of locations can be obtained if $H \leq (3/2)H_0$, [36].

4.4. Wind speed turbulence

Each deviation of the instantaneous value of wind speed from its average value within the corresponding 10 min interval represents turbulence. The causes of turbulence are obstacles on the soil surface, roughness of the terrain, and local dynamic variations of the air pressure and temperature. For this reason, vector of the wind speed should be regarded as a spatial vector of the time varying direction and intensity, therefore, it is possible to define: the longitudinal, lateral, and vertical components of the wind turbulence. For the selection and energy production of wind turbine, of special interest is the longitudinal component of the turbulence.

As a measure of wind turbulence, intensity of turbulence I, defined as ratio of the standard deviation of wind speed σ and average wind speed V, is used. Intensity of turbulence can be calculated for each 10 min interval i according to the following relation:

$$I_i = \frac{\sigma_i}{V_i}. \tag{12}$$

4.5. Wind turbine energy production

The major wind turbine manufacturers give the actual power curve of their product in the technical note. The curve is usually given for a fixed air density (standard is ρ_0 = 1225 kg/m^3). In order to determine production power of a wind turbine for a 10 min interval, it is necessary to know the actual air density and wind

speed at the hub height of the selected wind turbine. In this analysis it has been assumed that the wind turbine was located at the place of the measurement mast. For each 10 min interval i, the corresponding wind speed V_i at the wind turbine hub height is calculated according to relation (11). Then, calculation of the corresponding effective wind speed is calculated according to the following relation [22]:

$$V_{effi} = V_i \left(\frac{\rho_i}{\rho_0} \right)^{1/3}, \tag{13}$$

where ρ_i is the actual air density at the hub height, calculated by relation (7). The electrical power of wind turbine for each 10 min interval i is estimated according to the following relation:

$$P_i = P_{power\,curve}(V_{effi}), \tag{14}$$

where $P_{power\,curve}(V_{effi})$ is the standard power curve of the wind turbine for the fixed air density ρ_0 = 1225 kg/m^3.

It should be mentioned that the previous approach to estimation of the production power is acceptable for a pitch-controlled wind turbine. For a stall-controlled wind turbine the power output predicted by a given power curve for the estimated wind speed V_i is calculated first, and then the power output is adjusted according to the following equation [22]:

$$P_i = P_{power\,curve}(V_i) \frac{\rho_i}{\rho_0}. \tag{15}$$

The average gross production power of a wind turbine (P_{avg}) for certain time period is estimated on the basis of the following relation:

$$P_{avg} = \frac{1}{N} \sum_{i=1}^{N} P_i, \tag{16}$$

where N is the total number of observed 10 min intervals in the analyzed period of time. In this study, the observation was made of N = 101952 10 min measurement intervals over the analyzed period of two years of the wind speed measurements.

The annual gross electricity production (AEP) of a wind turbine is calculated according to the following relation:

$$AEP = T \cdot P_{avg}, \tag{17}$$

where T = 8760 h.

The gross capacity factor of a wind turbine at annual level is calculated according to the following relation:

$$C_F = \frac{AEP}{T \cdot P_n} = \frac{P_{avg}}{P_n}. \tag{18}$$

5. Results and discussion

For the analysis of wind characteristics and wind energy potential of the South Banat region, the measurement data for the two year period 09/01/2009–08/31/2010 have been used. On the basis of the measured standard deviations of the speed and direction of the wind, the days of freezing of the anemometer and vane shafts have been identified. These measurement data have been rejected. A total of 22 days have been rejected (about 3% of the total two year period of measurements). Statistical processing of the data, comprising: the frequency of occurrence of wind speed and direction and the corresponding probability density function, wind rose, yearly statistics, monthly and diurnal variations in wind speed, has been carried out.

5.1. Wind speed distribution and wind power density

A histogram of the cumulative frequency distribution of the wind speed for the two years at three measurement heights (60, 40, and 10 m), which shows the percentage of time the wind speed exceeding certain value, is shown in Fig. 2.

The measurement location is characterized by a small number of calms as regards the wind. More than 75% of the time throughout the year wind speed at the height of 60 m is higher than 3 m/s (the limit 3 m/s is important since this is the cut-in speed of many commercial turbines). This means that, at the location of the measurement mast, the wind turbines would be operating more than 6500 h annually, if the wind turbine hub was at the height of 60 m. By increasing the hub height, the number of operating hours would increase. At the targeted location wind speeds above 20 m/s are rare. During the measurement period of two years, the top recorded 10 min average wind speed at the height of 60 m was 23.8 m/s, and the maximum wind gust was 31.1 m/s. This means that in the targeted region, the wind turbines would seldom be out of operation due to strong wind (the cut-out speed of many commercial turbines is 25 m/s).

Fig. 3 shows the frequency distribution of wind speeds at different heights and the corresponding Weibull distributions, relation (1). Parameters of the Weibull distribution have been calculated according to relations (2) and (3).

Weibull distributions describe very well the frequency distributions of the wind speed at the South Banat region, therefore this distribution can successfully be applied for the wind potential evaluation and calculations of the perspective wind turbine annual production in the targeted region. The Weibull scale parameter c varies from 4 m/s for the frequency distribution of wind speed at 10 m height up to 6.5 m/s for 60 m height. The Weibull shape parameter k varies from 1.31 for frequency distributions of wind speed at 10 m height up to 1.7 for 60 m height.

Tables 1–4 present the basic indicators of the wind energy resources in the South Banat region in terms of the wind rose sectors for all four measurement heights. Twelve-segment wind roses have been used, therefore, one sector of the wind rose covers 30° of the azimuth angle. Tables 1–4 indicate central angles of each sector calculated relative to the geographical north.

The marks in the tables have the following meanings:

V_{avg} (m/s) – average wind speed, c (m/s) – the Weibull scale parameter, k – the Weibull shape parameter, P_{avg} – average wind power density, f(%) – frequency of occurrence of wind direction, in percents of the total measurement time (2 years).

Ten-minute intervals with v_i < 0.5 m/s have been taken as calms and for these points the measured data concerning wind direction are not relevant.

By analyzing data of Tables 1–4 one can conclude that the two-year average wind speeds at 60, 50, 40, and 10 m heights are: 5.80 m/s, 5.46 m/s, 5.33 m/s, and 3.68 m/s, respectively. The wind rose of the South Banat is characterized by two dominant directions of the wind, southeast and northwest. The southeast wind (košava) has made the greatest contribution in the wind energy potential of South Banat. By analyzing data of Table 1, one can conclude that duration of košava (central angles 120° and 150°) at the measurement site, at 60 m height and over two years of measurements, is 41.3% (about 3600 h/year). The average speed of this southeast wind in the analyzed two years measurement period is 8.43 m/s at 60 m height, and the corresponding power density is 457 W/m^2. In addition to the southeast wind, a significant wind potential is due to the northwest winds (central angles 300° and 330°). Total duration of the northwest winds in the analyzed two years measurement period is 25.2% (about 2200 h/year) with the average speed of 6.16 m/s at the height of 60 m and the corresponding average power density is 185 W/m^2.

This wind rose, containing dominant winds of the opposite directions, is very suitable for wind farm design concerning wake effect.

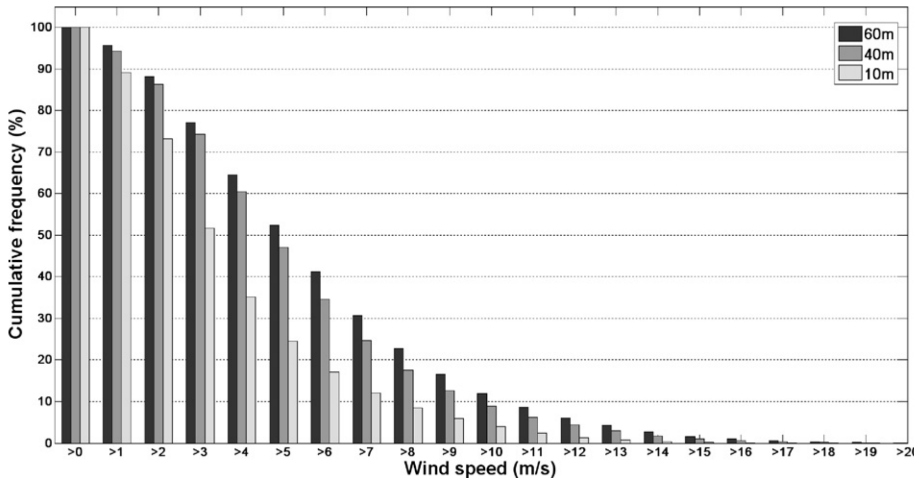

Fig. 2. Cumulative frequency distribution of wind speed for three measurement heights, over two years for Bavanište site (South Banat region).

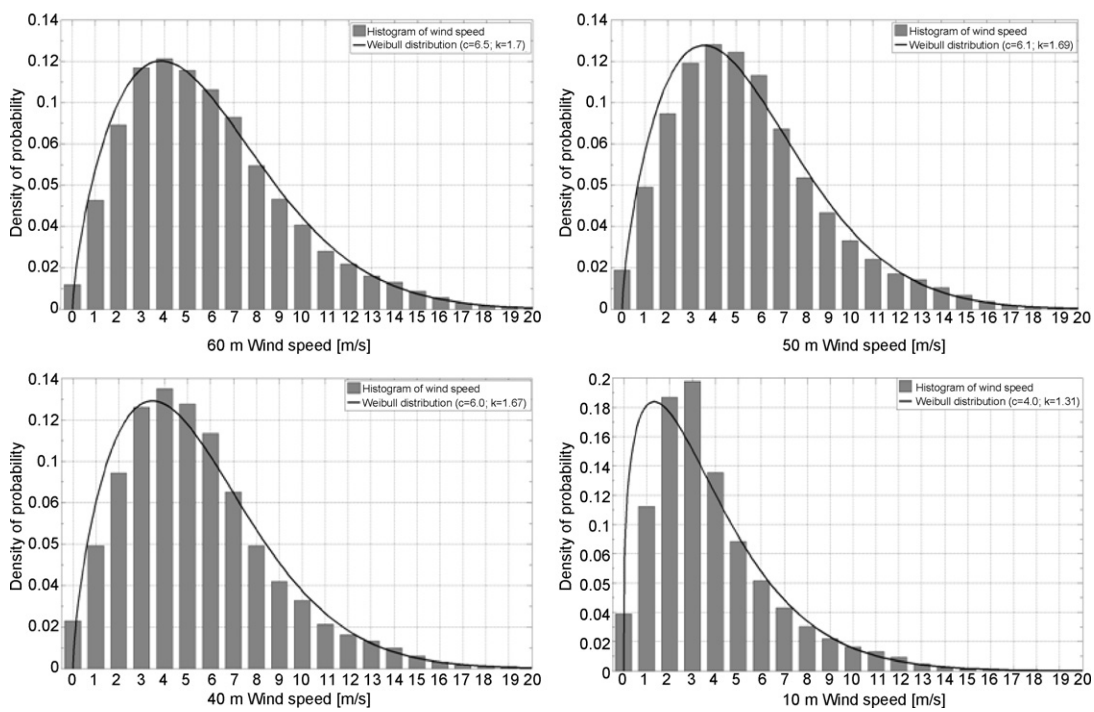

Fig. 3. Histograms of wind speed compared to Weibull distributions for the Bavanište site (South Banat region) over the two years measuring period.

Table 1
The results of statistical analysis of the measured data on wind speed at location Bavanište (South Banat) at 60 m level.

	The wind rose sector central angle (deg)												
	Calm	0	30	60	90	120	150	180	210	240	270	300	330	All
V_{avg} (m/s)	<0.5	4.51	4.15	3.26	4.21	8.31	6.08	3.26	2.58	3.49	5.02	5.56	5.24	5.80
C (m/s)	–	5.1	4.7	3.7	4.7	9.4	6.9	3.7	2.9	3.8	5.7	6.3	5.9	6.5
k	–	1.96	1.95	1.69	1.58	2.19	2.42	1.77	1.56	1.28	1.88	2.10	1.89	1.70
P_{avg} (W/m^2)	–	109	85	49	114	611	220	45	27	91	157	190	176	272
f (%)	1.2	5.0	3.5	2.6	4.5	25.0	16.3	2.8	2.0	2.9	9.2	16.2	9.0	100

Table 2
The results of statistical analysis of the measured data on wind speed at location Bavanište (South Banat) at 50 m level.

	The wind rose sector central angle (deg)												
	Calm	0	30	60	90	120	150	180	210	240	270	300	330	All
V_{avg} (m/s)	<0.5	4.33	3.87	3.09	4.01	7.72	5.64	3.13	2.42	2.96	4.65	5.32	5.01	5.46
C (m/s)	–	4.9	4.4	3.5	4.5	8.7	6.4	3.5	2.7	3.1	5.2	6.0	5.6	6.1
k	–	1.99	1.97	1.72	1.57	2.09	2.43	1.77	1.58	1.19	1.83	2.07	1.86	1.69
P_{avg} (W/m^2)	–	95	68	41	99	515	176	41	22	63	128	169	158	229
f (%)	1.9	5.0	3.4	2.5	4.5	24.7	16.2	2.8	2.1	2.8	9.1	16.0	8.9	100

Table 3
The results of statistical analysis of the measured data on wind speed at location Bavanište (South Banat) at 40 m level.

	The wind rose sector central angle (deg)													
	Calm	0	30	60	90	120	150	180	210	240	270	300	330	All
V_{avg} (m/s)	<0.5	4.19	3.75	3.05	3.94	7.54	5.58	3.06	2.39	2.88	4.39	5.09	4.90	5.33
C (m/s)	–	4.7	4.2	3.4	4.4	8.5	6.3	3.4	2.7	3.0	4.9	5.7	5.5	6.0
k	–	1.98	2.00	1.77	1.58	2.02	2.47	1.80	1.66	1.17	1.74	2.04	1.85	1.67
P_{avg} (W/m^2)	–	86	61	38	93	495	168	38	20	62	114	150	148	217
f (%)	2.3	5.0	3.4	2.4	4.5	24.6	16.1	2.8	2.1	2.8	9.0	16.0	8.9	100

Table 4
The results of statistical analysis of the measured data on wind speed at location Bavanište (South Banat) at 10 m level.

	The wind rose sector central angle (deg)													
	Calm	0	30	60	90	120	150	180	210	240	270	300	330	All
V_{avg} (m/s)	<0.5	2.96	2.40	2.03	2.64	5.43	3.72	2.23	1.70	2.08	3.10	3.63	3.64	3.68
C (m/s)	–	3.3	2.7	2.3	2.9	6.0	4.2	2.5	1.9	2.1	3.4	4.1	4.0	4.0
k	–	1.68	1.87	1.67	1.30	1.58	1.81	1.60	1.56	1.06	1.41	1.61	1.54	1.31
P_{avg} (W/m^2)	–	37	18	12	38	246	67	17	8	29	55	72	77	103
f (%)	3.9	4.9	3.5	2.6	4.4	24.1	15.8	2.9	2.1	2.9	8.6	15.6	8.7	100

Table 5
Average value of the wind turbulence intensity at the location of the measurement mast Bavanište, for different measurement heights, over two years measurement period.

Height (a.g.l)	60 m	50 m	40 m	10 m
$I_{(v>4\,\mathrm{m/s})}$ (%)	8.1	8.6	9.2	14.4

5.2. Monthly average value of the wind speed

Fig. 4 shows average wind speeds, month by month, for all four heights for the analyzed two-year measurement period.

In the South Banat region the winter months are far windier than the summer months. This annual profile of the wind speed is favorable from the electrical energy production point of view, since electrical energy consumption in winter is higher compared to the summer consumption [1].

5.3. Vertical wind speed profile

Fig. 5 shows comparative daily diagram of the wind speed variations at different heights at the location of the measurement mast at Bavanište. The diagrams have been obtained by averaging the corresponding 10 min wind speeds over two year measurement period.

During daytime, when the atmosphere is usually unstable, vertical increments of the wind speed are considerably smaller compared to those of overnight, when the atmosphere is stable.

Fig. 6 shows the 1 h average values of the wind share coefficient (α) obtained by averaging the corresponding 10 min values calculated on the basis of relation (10), for the analyzed period of measurements.

The South Banat region is characterized by a high wind speed increment with height. The average value of the wind share coefficient is 0.237. For this reason, in this region it is justified to use high masts for installing wind turbines.

5.4. Wind speed turbulence

By using relation (12) calculation of the intensity of wind turbulence at the site of the measurement mast Bavanište, for each 10 min interval, has been carried out. Table 5 shows the results of calculations of the average value of turbulence intensity at different measurement heights over the two year measurement period. Only the 10 min intervals where the wind speed was higher than 4 m/s were taken into account.

Fig. 7 shows diagram of the wind turbulence intensity at the height of 60 m as function of wind speed. It can be concluded that the targeted region is characterized by a low level of wind turbulence, amounting only 8.1% at the height of 60 m, which is favorable in so far as the efficiency and mechanical load of the perspective wind turbines in this region are concerned.

5.5. Wind turbine energy production

On the basis of the presented statistical analysis of the measured data and the analysis of the wind turbulence, it is concluded that according to IEC classification, the targeted region is characterized by the winds of class III. There are several manufacturers of wind turbines producing wind turbines for this class of wind.

For the purpose of verifying the wind potential at the targeted location, calculation of the annual electricity production (AEP) and the corresponding capacity factor (CF) for three wind turbine models, made by different manufacturers, has been carried out. The turbines are located at the site of the measurement mast. The calculations are performed for two wind turbine hub heights: 80 m and 90 m. The methodology described in Section 4.5 has been applied. The results are given in Table 6. The estimated values for AEP and CF in Table 6 are the gross values. For the purpose of the calculation of real (net) AEP it is required that the data of Table 6 are reduced by the amount of estimated losses which should include: the wind turbine downtime losses, wake losses, icing losses, power curve hysteresis losses, electrical losses (transformer and wiring losses), connection grid downtime losses, and other losses. These losses are calculated for each wind power plant separately. For a modern wind farm the total losses do not exceed 20% in the majority of cases [22].

By analyzing data of Table 6 it can be concluded that in the targeted region there exists technically usable potential of wind energy which can ensure economic feasibility of development of projects of the wind power plants. For the analyzed three types of wind turbines, the CFs between 30% and 35% have been obtained. AEP referred to the square meter of the wind turbine rotor (for 90 m hub height) is approximately the same for the Vestas V112 wind turbine (0.930 MWh/m^2 per year) and Siemens SWT 93 (0.924 MWh/m^2 per year), which are pitch-controlled, while it is somewhat lower for Alstom Eco 110 (0.900 MWh/m^2 per year) which is stall-controlled.

In the analyzed region there are many locations suitable for development of large wind farm projects (above 50 MW), which are

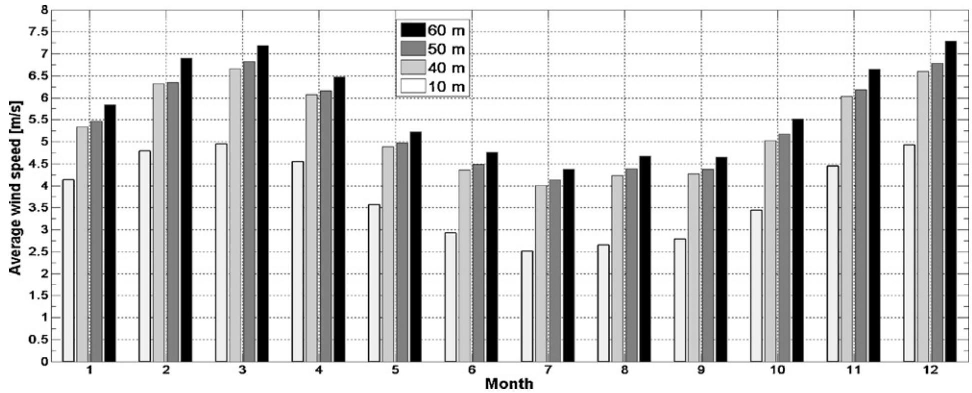

Fig. 4. Average monthly wind speeds at different heights at Bavanište site (South Banat region) over the period of two years.

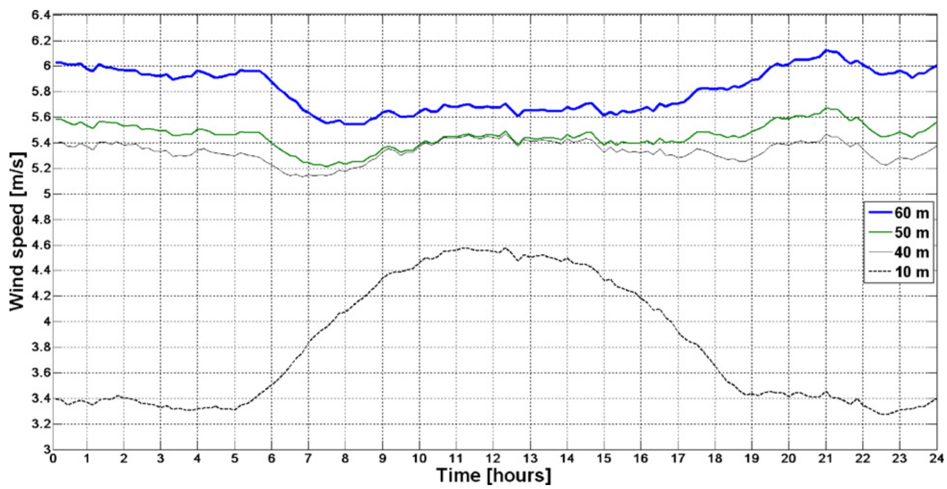

Fig. 5. Variations of wind speed at different heights at Bavanište site (South Banat region) for an average day over the period of two years.

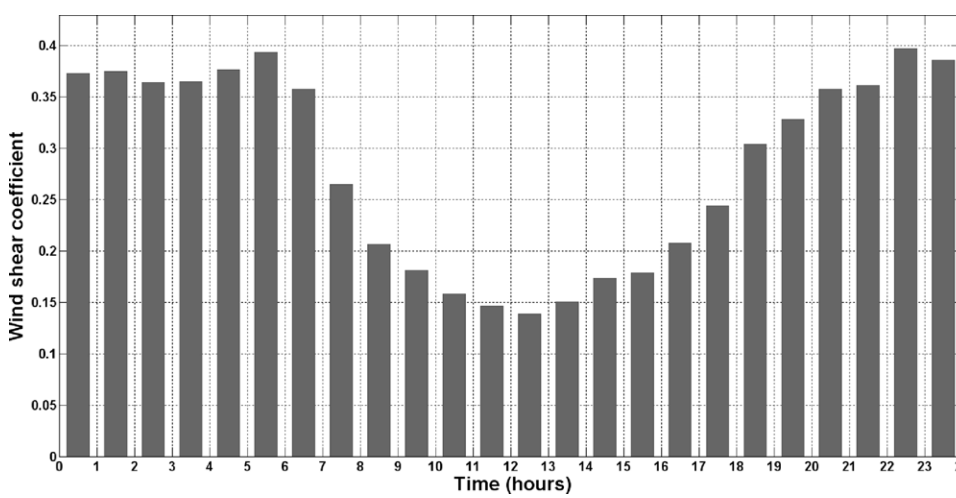

Fig. 6. One hour average values of the wind share coefficient (α) at Bavanište site (South Banat region) for an average day over the period of two years.

Table 6
The annual electricity production (AEP) and capacity factor (CF) for three wind turbine models made by different manufacturers at Bavanište site (South Banat region).

Wind turbine manufacturer and model	Rated power (MW)	Rotor diameter (m)	Hub height (m)	AEP (MWh)	CF (%)
Vestas	3.0	112	80	8817	33.6
V112			90	9160	34.9
Siemens	2.3	93	80	6030	29.9
SWT 93			90	6280	31.2
Alstom	3.0	110	80	8222	31.3
Eco 110			90	8550	32.5

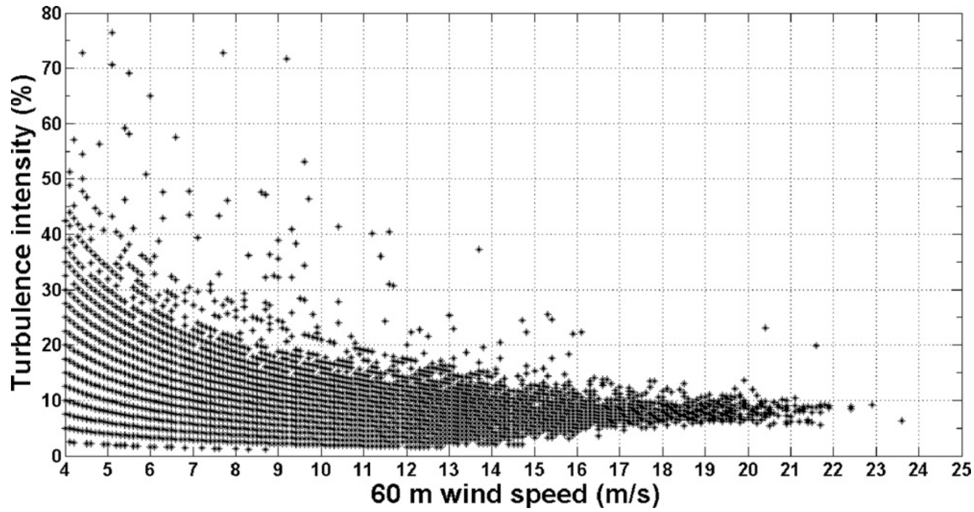

Fig. 7. Turbulence intensity of the wind at the height of 60 m as function of the wind speed.

characterized by a very accessible terrain having developed both road and electrical network (110 kV, 220 kV, and 400 kV) infrastructures which can ensure evacuation of the produced energy by the perspective wind power plants. In the targeted region, situated on the river Danube, is the hydro power plant Djerdap of installed power 1296 MW which enables economical balancing of the energy obtained from the perspective wind power plants in the South Banat region.

In the targeted region of South Banat there are quite a few relatively poor households which are isolated from the electrical supply network and the wind energy, in addition to developing large wind farms, can be used for driving small wind turbines and provide electricity for the isolated consumers in this region [37]. The wind energy in this region would also be significant if used for driving irrigation pumps, since 80% of the land in this region is of agricultural character and is used for cultivating wheat and other crops, therefore an irrigation system would increase the yield.

6. Conclusions

The investigations carried out in this work show that in the targeted South Banat region there is technically usable wind energy potential of class III. The basic properties of the wind energy in the targeted region are:

- Two year average wind speeds at heights 60, 50, 40, and 10 m are: 5.8 m/s, 5.46 m/s, 5.33 m/s, and 3,68 m/s, respectively.
- Weibull distribution describes very well the frequency distributions of the wind speeds at the South Banat region. The Weibull scale parameter c varies from 4 m/s for frequency distribution at 10 m height up to 6.5 m/s for 60 m height. The Weibull shape parameter k varies from 1.31 for the frequency distribution of wind speeds at 10 m height up to 1.70 for 60 m height.
- The wind rose of South Banat is characterized by two dominant wind directions, southeast and northwest. The southeast wind (košava) is the main carrier of the wind energy potential of the South Banat. Duration of košava at the measurement site, at the height of 60 m over the two year measurement period, is 41.3% (about 3600 h/year). The average speed of this southeast wind in the analyzed two year period is 8.41 m/s at the height 60 m and the corresponding average power density is 457 W/m^2.
- The targeted region is characterized by a very low level of wind turbulence intensity of only 8.1% at the 60 m height, which is favorable in so far as the efficiency and mechanical load of the perspective turbines in the region are concerned.
- Winter months are considerably windier compared to the summer months. The highest winds are in December and March and the lowest winds are in July. This annual profile of wind speed is convenient from the production point of view since the electrical energy consumption is higher during winter than during summer.
- The South Banat region is characterized by a strong wind speed increment with height. In this work a mathematical model for estimation of the vertical profile of wind speed, based on the minimum sum of least squares, is developed. On the basis of this model, the average value of the wind share coefficient is estimated to be 0.237. Therefore, it is economically feasible to use high wind turbine masts in this region.

An estimate of the gross annual production has been performed for three wind turbine models produced by different manufacturers. For all three models the annual capacity factor is between 30% and 35%. The annual production of electrical energy, referred to square meter of the wind turbine rotor (for 90 m hub height), is approximately the same for the Vestas V112 wind turbine (0.930 MWh/m^2 per year) and Siemens SWT 93 (0.924 MWh/m^2 per year), which are pitch-controlled, while it is somewhat lower for Alstom Eco 110 (0.900 MWh/m^2 per year) which is stall-controlled.

The South Banat region is a perspective region in so far as building wind power plants in Serbia is concerned. The basic characteristics favoring this region in terms of possible use of wind power are: good wind potential, good climatic conditions, accessible terrain, cheap transport of large wind turbines, relatively developed electrical transmission network which allows connections of large wind power plants, and, finally, the presence in the targeted region of the hydro power plant Djerdap which enables balancing production power of the perspective wind power plants.

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